CALIBRATION TRACEABILTY OF HIGH-RESOLUTION MEASUREMET SYSTEMS

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Abstract: *The article presents the traceability chains of one-dimensional measurements in the Laboratory for Technological Measurements as the holder of the national length standard. Some examples of calibration procedures are described, calibration of gauge blocks, calibration of precision probes, linear scales, grid plates and step gauges, and calibration of rings. Among all the possible errors that have been reviewed, the most important factors that determine measurement uncertainty are highlighted and their reduction is explained, such as compensation for thermal expansion of the material and geometric alignment of sensors. Among the wide range of verification methods based on different standards, the use of laser interferometry allows us to determine individual geometric errors and detailed properties of the calibrated measurand and instruments with high resolution.*

Key words: *Dimensional Metrology, High-resolution Measurement, Calibration, Measurement Uncertainty, Measurement Traceability*

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1. Introduction

The article provides a brief overview of the activities of our Laboratory for Measurements in Production and presents in detail the maintenance of measurement traceability. The laboratory operates at the Faculty of Mechanical Engineering within the Slovenian distributed metrology system under the coordination of the Metrology Office of the Republic of Slovenia (MIRS) and provides services in the field of industrial and scientific metrology and a quality management system, which includes calibration of standards and professional training.

Its primary task is to maintain the national length standard and ensure the traceability of measurements in Slovenian industry. For this purpose, the laboratory was accredited by the Slovenian accreditation body (SA) for the calibration of length standards and measuring instruments in accordance with the SIST EN ISO/IEC 17025 standard. The scope of accreditation has been expanded several times and currently covers 24 calibration procedures (Annex to the accreditation certificate LK-003, SA). Key Calibration and Measurement Capabilities (CMC) are accepted into the Key Comparative Data Database (KCDB) within the International Bureau of Weights and Measures (BIPM). For all calibrations within our scope of operation, we issue an accredited certificate with the logo of the accreditation body SA, and CIPM MRA in the case of a calibration procedure included in the KCDB database.

In cooperation with domestic and foreign companies and research institutions, we participate in numerous research projects with industry, development projects and interlaboratory comparisons (BIPM, EURAMET, LABCOM). Traceability of calibration measurements is ensured by regular calibration of standard equipment at accredited institutions (PTB, METAS, IMT, LMK…) and by an internal chain of accredited procedures, which is presented in this article.

While industry is constantly facing with demanding challenges in terms of accuracy and complexity of measurements for providing tolerances on micrometer levels (Vukelic et al., 2024; Yin et al., 2024; Demircioglu et al., 2024; Kramar et al., 2025), there is continuous development of measurement systems with high-resolution sensors and coordinate measuring equipment that must be regularly calibrated with precise mechanical and optical standards in well controlled laboratory conditions (Carmignato et al., 2020; Li et al., 2024; Klobucar et al., 2017; 2019; Safaric et al., 2021; Acko et al., 2024).

This article presents some calibration process chains in our laboratory and discusses the influential factors for improving measurement accuracy.

2. Measurement uncertainty

The measurement uncertainty is usually given by the calibration result with ±, denoted as U, expressed as an expanded uncertainty (corresponding to twice the standard uncertainty u), which gives a 95% confidence level for a normally distributed measurement, according to the Guide to the Expression of Uncertainty in Measurements prepared by the Joint Committee for Metrology Guidelines – BIPM.

To determine the uncertainty for a calibration procedure, the analysis includes an evaluation of all possible errors. It generally includes environmental influences (such as thermal deviations from standard air and material temperatures and the quality of the sensors), mechanical influences (such as the quality of surface contacts), geometric influences (such as the alignment of the measurand with length sensors, whether optical or mechanical), and indication (resolution of the display). The total measurement uncertainty is calculated as the root of the sum of the squares of the partial contributions (Eq. 1.a). The sensitivity coefficient c_i is evaluated as the degree of influence of the partial error. It includes the results of the last calibration certificate (deviation in indication, calibration uncertainty) and any future drift (estimated based on past certificates).

$$U = 2 \times u = 2 \times \sqrt{\sum_i (c_i \times u_i)^2} \quad (1.a)$$

$$u_{\text{measurement}} = \sqrt{u_{\text{measurand}}^2 + (u_{\text{measurand}}/2)^2} \quad (1.b)$$

Reference used in the calibration shall be accurate enough to have a negligible effect on total uncertainty of the measurement system. Depending on the equipment applied, different terms are involved, and demand focus to maintain a required precision level. If the measurement accuracy is twice that of the measurand, the result is only one-tenth less accurate than the measurand (Eq. 1.b), in such case the measurement uncertainty is practically negligible.

3. Traceability chains

The basic length standards in most industrial companies are gauge blocks, made of steel, ceramics or carbide, the most accurate material standards with a certain length between two parallel measuring surfaces, with quality classes 00, 0, 1 and 2 (standard SIST EN ISO 3650:2000). Used for calibrating length measuring instruments and for adjustments in all branches of manufacturing, they are important basis for maintaining traceability in dimensional metrology. Their important property is that they can be wrung with low dimensional uncertainty, when taking care of influencing factors, such as the quality of the gauge blocks (grade, wear), surface preparation (cleaning and usage of a lubricant), wringing (way and time, temperature of hands and using gloves). For measurements at the micro level, temperature stabilization is recommended (Lipus et al., 2022).

Our laboratory performs the calibration of such blocks by mechanical probing, using the comparator in the measuring range of (0.5 – 100) mm (Fig. 1.a) and the comparator for longer blocks up to 1000 mm (Fig. 1.b). The difference between the reference block and the block being calibrated is measured at the central point of block’s surface with expanded uncertainty given by Eqs. 2, for different material in the range (0.5 – 100) mm. The measuring range of the inductive probe is ±2 µm, and the resolution is 0.01 µm. Before starting each calibration, we also perform a surface flatness check with a plane-parallel glass cylinder.

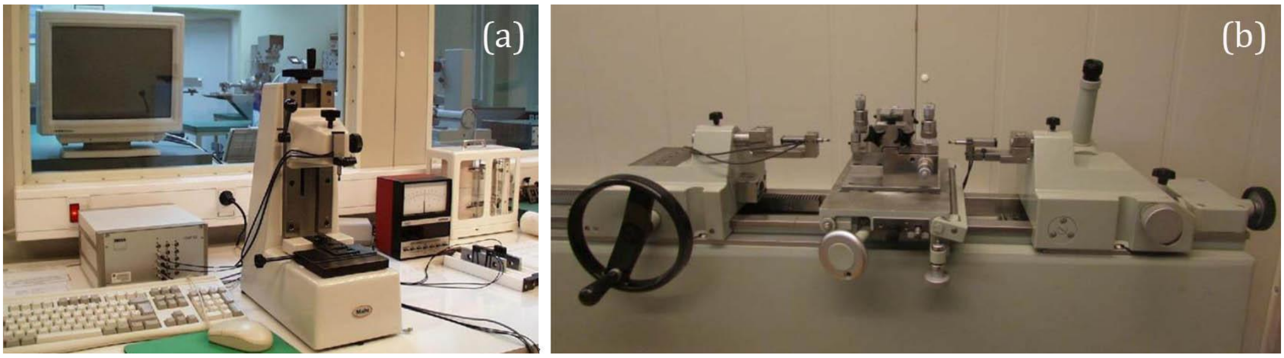

Fig. 1. Comparators for blocks: (a) with length (0.5 – 100) mm, (b) (125 – 1000) mm

To ensure the measurement traceability for the calibration of high-resolution length-measurement systems, a primary set of steel gauge blocks of the highest-grade K is maintained, periodically calibrated at one of the European national laboratories with high-precision laser interferometry. The comparator is periodically checked by the comparison method of pairs from the primary set, performed in the laboratory chamber to include possible influence of relatively well-controlled air condition (i.e. pressure, humidity changes and the most influential temperature within a deviation (0.1 to 0.3) K from the standard 20 ^{0}C). When calibrating the steel blocks, the residual temperature difference between calibrated and reference blocks (with the same nominal length, after over-night temperature stabilization under well-controlled atmospheric conditions and using high-precision material temperature sensor with an accuracy ±0.02 K) contributes noticeably to the second term in Eq. 2.a, while the first term is mainly determined by deviation of surface quality of the calibrated block from the reference block. In the case of calibration of ceramic or carbide blocks, a further noticeable increase in the second term is due to difference in coefficients of thermal expansion; i.e. $11.5 \times 10^{-6}/\text{K}$ for the reference steel blocks, $4.4 \times 10^{-6}/\text{K}$ for tungsten carbide and $9.4 \times 10^{-6}/\text{K}$ for the ceramic blocks. In the case of longer blocks, a precise alignment is crucial to reduce the tilt deviation (Fig. 1.b). The thermal expansion being proportional to the blocks' length increases the calibration uncertainty by up to 0.5 µm (calculated for 1000 mm steel block).

$U = \sqrt{(35\ \text{nm})^2 + (0.5 \times 10^{-6} L\ )^2}$ for calibration of steel blocks (2.a)

$U = \sqrt{(50\ \text{nm})^2 + (0.55 \cdot\times L\ )^2}$ for calibration of ceramic blocks (2.b)

$U = \sqrt{(50\ \text{nm})^2 + (0.9 \times 10^{-6} L\ )^2}$ for tungsten carbide blocks (2.c)

where L is the length in meters.

On such way calibrated secondary sets (grade 0) are used as reference in calibration procedures on three-dimensional machines (3D-CMM), one-dimensional coordinate measuring machines (1D-CMM) and measuring tools. Most of calibration procedures accredited in our laboratory are performed in a well-controlled climate chamber, on a Newport precision alignment table, using temperature sensors with expanded uncertainty 15 mK for material and 50 mK for air to ensure high compensation for thermal length expansion.

High-resolution measurements are performed with laser interferometry. The laser frequency is calibrated by comparison with primal frequency standard approved by BIPM and accepted as national standard for length by SA (Lipus et al., 2016). The uncertainty of length measurements using interferometry strongly depends on the temperature stabilization and quality of the air sensors along the measurement path (Lipus et al., 2021; 2024). The expanded uncertainty of laser interferometry under well-controlled chamber conditions (with air parameter variations of ±0.1 hPa, ±0.1 K and ±15% humidity) is $0.4 \cdot\times L$ and under our laboratory air conditioning (±0.5 hPa, ±0.5 K and ±15%) is $0.6 \cdot\times L$.

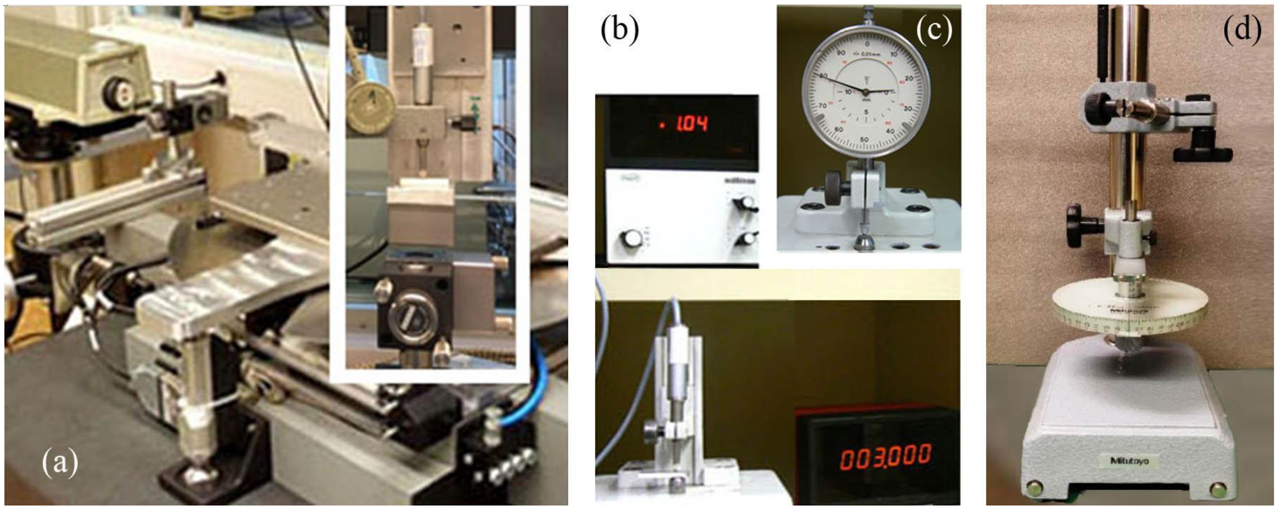

Fig. 2. (a) Calibration of a precise probe, (b) Calibration of a dial indicator tester (c) Calibration of a dial gauge, (d) A dial indicator tester with analogue display

An example of a measurement chain in our laboratory is shown on Fig. 2. Precision probes are calibrated with expanded uncertainty by Eq. 3 (for length up to 100 mm). A precision probe is used, for example, to calibrate gauges with an expanded uncertainty determined by Eqs. (4). The first term depends strongly on the resolution of the tester's display. The second term depends on material expansion, assuming the maximum temperature difference between the gauge block and the dial indicator tester ±0.2 K, stabilized under well-controlled laboratory conditions with a maximum permissible air temperature fluctuation of (20±0.5) ^{0}C. Similarly, Eq. 5 is evaluated for calibration of dial gauges. The second term is the same under the same air conditioning, while the first term is calculated for the best case when both (indicator and dial gauge) having digital 1 µm resolution. Higher accuracy of the dial gauges can be achieved by direct calibration with laser interferometer (Eq. 3), if requested by a customer.

$$U = \sqrt{(30\text{ nm})^2 + (1.1 \times 10^{-6} L)^2}\text{; for calibration of precise probes} \quad (3)$$

$$U = \sqrt{(0.1\text{ µm})^2 + (2.5 \times 10^{-6} L)^2}\text{; the digital with 0.1 µm resolution} \quad (4.a)$$

$$U = \sqrt{(0.25\text{ µm})^2 + (2.5 \times 10^{-6} L)^2}\text{; the analogue with 1 µm resolution} \quad (4.b)$$

$$U = \sqrt{(0.6\text{ µm})^2 + (2.5 \times 10^{-6} L)^2}\text{; the digital with 1 µm resolution} \quad (4.c)$$

$$U = \sqrt{(0.9\text{ µm})^2 + (2.5 \times 10^{-6} L)^2}\text{; the digital with 1 µm resolution} \quad (5)$$

Another example of chains in our chamber is sub-micrometre precise calibration of line scales (Eq. 6), and of two-dimensional grid plates (Fig. 3.a). After proper alignment of the entire mechanical and interferometry displacement system, the geometrical errors of the interferometer system (the cosine, Abbe and the death path errors) are negligible, while the camera positioning error (the resolution and Abbe error) contributes at the level of a few tens of nanometers.

$$U = \sqrt{(90\ \text{nm})^2 + (1.1 \cdot\times L\ )^2};\ \text{for calibration of line scales} \tag{6}$$

$$U = \sqrt{(100\ \text{nm})^2 + (0.5 \times 10^{-6} L\ )^2};\ \text{for calibration of step gauges} \tag{7}$$

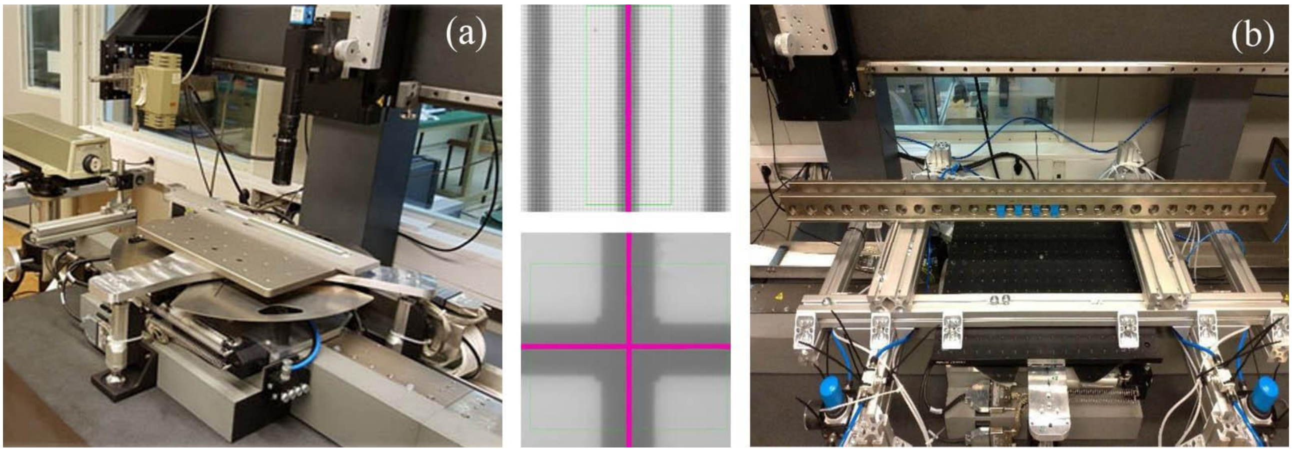

Fig. 3. (a) Calibration of a line scale and a two-dimensional grid plate, (b) Calibration of a step gauge

The presented setup is also applied for calibration of step gauges (Fig. 3.b), which consist of a sequence of numerous measuring surfaces as a precise standard for the calibration of coordinate measuring machines. The step gauge is clamped on a Newport table and aligned, the table movements are controlled by a computer program, and the shifts to the double-sided inductive sensor are measured by a laser interferometer, step by step for each surface of the step gauge. By installing multiple temperature sensors along the calibration path to accurately compensate for the temperature expansion, the second term in Eq. 7 is properly reduced on the level of gauge blocks' calibration, while the first term is mainly determined by the alignment of the table and the probe.

In our laboratory, laser interferometry is used to improve the calibration accuracy of coordinate measuring machines. On the three-dimensional coordinate measuring machine, it is improved by determination of probe inclination (the difference between the measured distance by laser interferometry and the reference diameter), as shown in Fig. 4.a, which leads to a lower first term in Eq. 8 for two-point determination of ring diameter. On a one-dimensional machine, it is used to measure the probe displacement on the surface of the measurand (Fig. 4.b), which gives the uncertainty with Eq. 9.

$$U = \sqrt{(0.2\ \mu\text{m})^2 + (2.8 \times 10^{-6} L\ )^2};\ \text{for ring diameter on 3D-CMM} \tag{8}$$

$$U = \sqrt{(0.6\ \mu\text{m})^2 + (3.0 \times 10^{-6} L\ )^2};\ \text{for ring diameter on 1D-CMM} \tag{9}$$

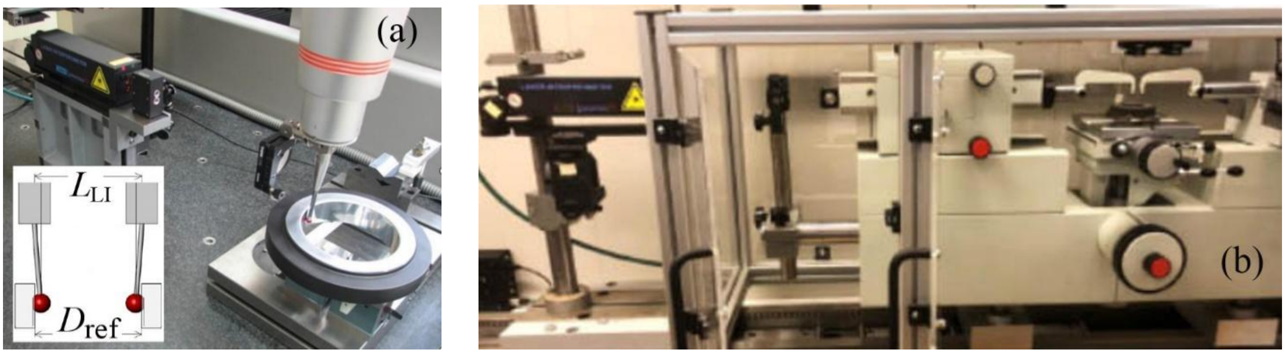

Fig. 4. (a) Determination of probe inclination of 3D-CMM, (b) Calibration of ring diameter on 1D-CMM with laser interferometry

4. Conclusion

As the holder of the national length standard, the Laboratory for Technological Measurements ensures the traceability of measurements at the highest level in the Republic of Slovenia. It continuously carries out research projects and comparisons with other national institutes and accredited laboratories, thereby improving measurement methods to ensure appropriate accuracy within calibration chains and to meet the growing demands for quality control of production processes in the Slovenian industry and the needs of other accredited calibration laboratories. In most of the precise calibration procedures developed in our laboratory, temperature stabilization and material expansion compensation, as well as geometric alignment of mechanical and optical sensors, have been proven to be the most important influencing factors, and are therefore the main subject of current and future research to further improve the calibration accuracy. For example, the development of a new method for vertical alignment of a precision probe using a digitally controlled video system is underway, which will also be applicable in a real production environment. Recent challenge in our laboratory is the development of calibration of infrared laser interferometers, which are increasingly used in manufacturing processes due to their high portability, but are not yet included in the international traceability metrological system.

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